RENDEZVOUS RADAR FOR SPACE SHUTTLE ORBITER VEHICLE

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Summary. To successfully complete many of the Space Shuttle Program proposed missions involving Orbiter rendezvous with orbiting satellites, some method of detecting and tracking remote targets is desirable. Several studies to establish the requirements for a rendezvous radar system indicated the feasibility of the concept. Extensive application of state of the art components is possible, and system parameters can be determined in a general sense to avoid impacting Orbiter development. Considerations of size and weight are necessary to the choice of any system, as well as the operational capabilities of the candidate. Two radar systems appeared to meet the requirements: a microwave radar and a laser radar. Although the laser radar was highly competitive, difficulty was encountered in assessing the operational risk of such a system. The microwave radar was therefore selected as the rendezvous sensor most suitable for Space Shuttle Program use.

Introduction. Among the multipurpose functions of the Space Shuttle Orbiter is the routine rendezvous of the vehicle with a variety of orbiting spacecraft. In addition, rendezvous is accomplished over a broad range of orbit parameters. A high level of operational flexibility can be obtained with the use of a sensor that facilitates rendezvous with minimum ground assistance. The Orbiter is the active, maneuvering vehicle so that the effect of using a sensor is to limit fuel consumption during rendezvous maneuvering to a level compatible with the Orbiter reaction control system (RCS).

The evaluation of a sensor for rendezvous use is the result of a series of design studies that investigated the expected performance of microwave radar and laser sensor systems, passive and cooperative targets, navigation system errors, specific model mission requirements, installation limitations on the Orbiter vehicle, and the parameters to be measured by the sensors plus the required measurement accuracies. The conceptual design of a microwave radar based on these elements is discussed in this presentation. The sensor design has been carried only to the point of determining the installation and performance impact on the Orbiter. Some subjective judgments in selecting a rendezvous sensor concept were inevitable, since the reconciliation of claims of improvement in the state of sensor art with overall Orbiter program goals is not always definable in quantitative terms.

This discussion presents the basis for the use of a rendezvous sensor on the Orbiter and the development of the sensor operational requirements, followed by the results of a trade study to select a sensor concept. Since a requirement for detecting and tracking passive targets, independent of ground assistance and ambient lighting conditions, is basic, the trade study was narrowed to a comparison of microwave and laser (optical) radar systems in the "skin" tracking mode. A microwave radar was selected.

Characteristics are described for a radar system that will meet Orbiter requirements, considering target models, mission parameters, installation constraints, and the limitations of available technology. Radar parameters were defined in as general a way as possible to give wide latitude in selecting a realistic design. The result is a description of the significant installed system characteristics.

Why a Rendezvous Sensor for Shuttle Orbiter? The large number and variety of missions envisioned for the Shuttle Orbiter leads to the conclusion that missions requiring rendezvous with unmanned satellites must be as independent of ground assistance as feasible. Independence can be obtained in large degree by an autonomous navigation system on the Orbiter. However, reasonable autonomous navigation requires periodic updating during a mission, and time to perform updating is not always available. This indicates that a requirement for an onboard rendezvous sensor would be advantageous to preclude excessive fuel consumption or the possibility of incomplete rendezvous.

For each instance during which rendezvous with an unmanned satellite is a primary Orbiter mission requirement, a time is imposed for rendezvous completion. The constraint is not severe or even limiting for some missions, but in the case of one specific mission, the time available to complete rendezvous is short by space operating standards. The time-constrained mission, which for study purposes is designated Mission III-B, requires the retrieval of an unmanned satellite in a single orbit. Mission III-B is commonly referred to as the "once-around mission" in that the Orbiter is launched in a polar orbit, retrieves an unmanned satellite, deorbits, and lands in essentially one revolution around the earth. The are shown diagrammatically in Figure 1. Consideration of the detailed mission time line indicates dramatically the the accomplishment of rendezvous.

A summary of the time history of the dynamic parameters for Mission III-B is given in Figure 2 for one case of navigation system errors. The case illustrated in Figure 2 is pessimistic and is used for illustrative purposes. From the data in the figure, however, basic radar system parameters can be deduced, since the angle uncertainty of the target relative to the Orbiter increases rapidly as the range to the target decreases. Thus, short-range detection requires large angular search in a short time. To decrease angle search requirements, detection range should be as large as possible. But mission events after insertion, which are not shown in the figure, preclude radar operation prior to a range of approximately 7.5 nautical miles, that is until 4 minutes after insertion. The time available for target detection and acquisition is limited. Without a rendezvous sensor, target location and Orbiter control to effect rendezvous would have a low probability of success.

The second type of rendezvous, which is not nearly so time-constrained, is essentially a multiple orbit, coplanar maneuver and is initiated at a range between 200 and 300 nautical miles. A typical relative motion plot for long-range rendezvous is presented in Figure 3. Since an active sensor capable of detecting a target at 300 nautical miles would be excessively large, this type of rendezvous with passive targets depends on optical detection and tracking during the initial phases of rendezvous. The optical tracker is not a separate instrument but rather one of the star sensors on the Orbiter whose primary function is navigation system updating. It detects and tracks targets in angle only using reflected sunlight. Rendezvous is therefore initiated on the assumption that the target is sunlit. Because the star sensor is useful only when the target is illumiated by the sun, at some range it is necessary to switch to an active sensor for the terminal phase of rendezvous. If the target is not sunlit at initiation, it is possible to start rendezvous at long range from ground-supplied target information and navigation system update. An active sensor is then extremely useful during the terminal phase of rendezvous in reducing RCS fuel consumption. The effect of sensor range on RCS fuel use is shown in Figure 4. From Figure 4, it can be seen that a sensor detection range of approximately 30 nautical miles imposes a small increase in ΔV requirements, but if the detection range is shorter than 10 nautical miles the ΔV requirements increase rapidly. Since a change in Orbiter velocity of one ft/s uses approximately 28 pounds of RCS fuel, a sensor detection range between 10 and 30 nautical miles is advantageous. The values given in Figure 4 are not absolute; they vary depending upon the model selected for the onboard navigator and the time from the last navigation system update.

Of significance in sensor performance requirement definition is the rate at which angle errors build-up as a function of range from the Orbiter to the target for the terminal phase of long-range rendezvous. The dynamics leading to the data in Figure 4 are based on an angular build-up rate (Figure 5). It can be seen that at ranges greater than 12 nautical miles the angular error is quite small, but as range decreases the angle uncertainty in target location increases rapidly. For short range detection, it is again necessary for a sensor to search large angle uncertainties “to find” the target.

For those missions during which rendezvous is to be accomplished without ground assistance, a cooperative rendezvous sensor mode must also be provided. The cooperative mode requires a beacon-transponder on the target for long-range detection and tracking.

The angle uncertainties of target location and consequent fuel penalties associated with rendezvous indicate the utility of a rendezvous sensor. However, additional considerations fortify the functional utility of a sensor that measures the spatial coordinates of the target relative to the Orbiter and the rate of change of the spatial coordinates. In theory, the rendezvous phase can be conducted automatically under the control of the central computer of the Orbiter once the target is acquired and tracked by the rendezvous sensor. However, in actuality, the rendezvous is conducted under the supervision of the Orbiter crew at short range where velocity changes are used to slow the Orbiter to zero relative velocity with respect to the target. Maneuvering the Orbiter relative to the target may also be necessary at short range to obtain the correct position for docking.

Sensor measurements most useful for optimizing the man-machine interface are difficult to establish analytically. Therefore, a man-in-the-loop simulation study was conducted at the NASA L.B. Johnson Space Center to define quantitative limits on rendezvous sensor performance. A concomitant to rendezvous sensor performance definition was the demonstration of the ability of astronauts to achieve rendezvous with the aid of a properly configured sensor.

Sensor Performance Requirements. Analytical study results, sensor performance capabilities, and man-in-the-loop simulation have been combined into a set of performance requirements. The sensor requirements for passive target rendezvous are summarized in Table 1. These requirements were not established in one step but represent the results of an iterative process. This is perhaps best illustrated by the detection range requirements for long-range rendezvous. From Figure 4, it is obvious that a sensor detection range of approximately 60 nautical miles would conserve RCS fuel. A sensor for passive detection of a reasonably sized target at this range would impose a severe penalty on the Orbiter. Since detection at 30 nautical miles requires only a modest increase in RCS fuel, a reduction in sensor performance of 12 dB results because of the inverse fourth power dependence on range. But a sensor configured for 30 nautical miles detection could not be installed on the Orbiter without major impact. Further study established that the RCS fuel capacity on the Orbiter was sufficient to support rendezvous maneuvers for a sensor detection range which resulted in good measured data at 10 nautical miles. The sensor to support a 10-nautical-mile range could be installed on the Orbiter vehicle and this value was adopted.

The parameter measurement accuracies given in Table 1 are in terms of random and bias errors. The types of errors are distinguished primarily by their expected duration. For specification purposes, bias errors are considered to be those measurement errors that are constant over a period of time of sensor operation.

Table 1. Rendezvous Sensor Performance Requirements

Measurement or System Characteristic	Requirements	How Established
Angle search limits	±50 deg about LOS - 2 axes	• Computer studies: III-B and Baseline Navigator • Orbiter limit cycle • Deployment bias • Navigation system designation accuracy
Detection - acquisition range	10 - 12 nm	• Computer studies • Navigation system accuracy • Expected target size
TRACKING PARAMETERS - Accuracies are 3σ		
Range	10 nm to 100 ft ±0.01R	• Range rat e accuracy requirements • Computer studies • Man-in-the-loop simulation at JSC
Angle (±10 deg about LOS)	±10 mr random, 60 mr bias*	• Man-in-the-loop simulations at JSC • Angle rate accuracy requirements • Computer studies
Range rate	±1 ft/s	• Man-in-the-loop simulation at JSC
Angle rate	0.14 mr/s	• Man-in-the-loop simulation at JSC
*Bias error of 3 degrees (60 mr) imposes increased RCS weight of 112 pounds.		

What Form of Rendezvous Sensor is Optimum? From the sensor requirements for both passive and cooperative targets, the detection problem associated with target location uncertainties, the parameters to be measured, and the required measurement accuracies, no single optimum approach to rendezvous sensor selection is obvious. Claims can be made for a variety of sensing techniques, but for passive target detection and tracking with measurement of range and range rate as well as angle parameters, straightforward solution to the rendezvous sensor problem appears to be a microwave radar patterned after a conventional airborne fire control radar. The technology of fire control radar is highly developed and meets substantially all of the rendezvous sensor requirements. However, in an operational system the penalty in size, weight, and power imposed by the rendezvous sensor may be sufficiently large that alternate techniques could be advantageous.

The operational flexibility afforded by a “skin” tracking mode (target surface reflection) narrowed the field of suitable sensor types to a choice between a microwave radar and an optical radar based on laser technology. A detailed trade study was performed to establish a basis for a selection. The results favored a laser radar if such a system is considered realistic. Efforts to obtain assurance that an advanced laser radar does not represent high technical risk were not fruitful, so the microwave radar was selected.

The trade study conclusion was enhanced by the emergence of wideband data communication requirements for the Orbiter. Data rates postulated for wideband communications were sufficiently high that the use of a high-gain antenna on the Orbiter is necessary to constrain transmitter power. Later studies determined that the use of a common high-gain antenna for the rendezvous radar and high data rate communications is feasible and that the selection of a microwave radar afforded an advantageous growth potential for the equipment on the Orbiter.

In a short report it is not possible to discuss the detailed design studies which isolated the trade factors between microwave and optical radar. However, a competitive laser radar design concept emerged based on heterodyne detection. Heterodyne laser radar systems are conceptually identical to microwave systems with the distinction that in the optical portion of the spectrum different techniques are used to obtain equivalent effects. The flexibility of design afforded by optical technology is available to the optical (laser) radar designer. A truly lightweight laser radar using CW transmission evolved as the basic competitive approach with a microwave radar.

The CW laser radar system is a relatively straightforward design based on a radiated power of 5 watts. An optical schematic of a CW laser radar is shown in Figure 6. The operating wavelength is 10.6 microns because of available CO_2 sealed-off lasers. A common aperture is used for transmission and reception (transceiver) and coherent heterodyne detection is used. Local oscillator power for heterodyne detection is obtained from a separate laser. The local oscillator is locked to the transmitter to maintain temporal coherence. The local oscillator is also used to remove the Doppler frequency from the received signal. This is necessary to reduce the IF bandwidth, since Doppler sensitivity is high at a wavelength of 10.6 microns, of the order of 62 kHz/ft/s. The characteristics and performance of the CW heterodyne laser radar are given in Table 2.

Ranging is accomplished by linear FM modulation of the transmitter and local oscillator. The frequency modulator is a piezoelectric crystal which mechanically modulates the length of the laser cavity. It is a commonly used approach in laser communications systems but has yet to be demonstrated as a useful ranging technique in CW laser operation for

Table 2. Coherent CW Laser Search and Track Radar Characteristics and Performance Summary

Item	Characteristics
Baseline System	
Operating wavelength	10.6μ
Laser power	5 watts
Detector quantum efficiency	0.25
Laser power X aperture area	0.05 watt M^2
Weight (telescope/gimbal)	25 lb
Detector temperature	78°K
Size	8 x 12 x 18 in.
Performance	
Search/detection	S/N ≥ 17 dB T/N = 13.5 dB
Track	
Angle accuracy	< 1 mrad
Range accuracy	<< 100 ft
Range rate accuracy	< 1 ft/s
Margin	
Detection probability = 0.99	- 5.2 dB
Detection probability = 0.90	- 8.2 dB

long ranges. Time of flight considerations require range compensation of the receive optics. This is accomplished internally by a driven mirror.

Two-dimensional angle scanning is achieved by a scanning mirror in one axis and a gimbal drive in the orthogonal axis, which produces a raster scan with variable spacing between scan lines. Scan rates and acquisition times can be held to a reasonable level for extended targets, This follows from the narrow beamwidths encountered in optical systems with the result that targets are generally larger than the beamwidth for ranges shorter than 30 nautical miles. This condition is opposite that of the microwave radar for which the target is considered a point source during detection. At optical frequencies a 10-cm aperture has a beamwidth of 0.1 milliradian or less. At a range of 10 nautical miles, the beam diameter is approximately two meters, and large targets may subtend several beamwidths. Thus a spaced or nonoverlapping raster scan can be used in the search mode.

Power calculations are based on a target reflectivity of 20 percent and diffuse (Lambertian) scattering. But real targets may be specular so that diffraction produces a lobed model. A significant increase in laser system performance would be required for specular targets. Before a laser radar is selected it would first be necessary to obtain actual target scattering data.

Trade Study Results. It was established that the CW laser radar approach is highly competitive with the microwave radar in meeting the requirements of the rendezvous sensor in the skin track mode. The system in Figure 6 is flexible, lightweight (less than 100 pounds) and low power. It is based on available CO_2 laser technology and longwave IR optical tracker technology. It requires cryogenic cooling of the detector for high quantum efficiency, although cooled optics are not required. When compared with a microwave radar, however, it has a high technical risk. This conclusion is based on the data in Table 3, which is a summary of the comparison of laser and microwave technology.

Design Constraints. A radar system design represents a series of design compromises. The resulting design meets operational requirements to the extent that these requirements are also subject to adjustment as the characteristics of the Orbiter and its subsystem are more fully defined. However, in a concept as complex as the Orbiter, it is frequently necessary to start with a set of operational conditions and uses in order to proceed with a system design. One of the first orders of priority in the development of the Orbiter is a realistic definition of each operating subsystem, so as to properly aportion space and power and to control total Orbiter weight. Early definition of subsystem characteristics is then basic to the orderly development of the Orbiter vehicle.

In performing this task, it is to be expected that an iterative approach is essential, because an early subsystem concept may be displaced by a modification of requirements or by the use of alternate design approaches. Thus, the rendezvous sensor approach discussed is a first order design to establish general sensor subsystem characteristics without precluding alternate approaches. In specific areas of parameter measurement, actual mechanizations are considered and the measurement results compared. Significant parameters are identified for the purpose of determining the installation impact on the Orbiter.

Radar Target Model. The design of a sensor requires a definition of what is to be sensed. For microwave radar a target is defined in terms of its radar cross section. For targets that are large relative to wavelength, the statement of a radar cross section implies an average cross section, since for large targets interference effects produce a lobed structure. Consequently, the reflectivity pattern of most targets is a function of aspect angle. This effect is present to some extent in all distributed targets, except for spherical shapes. A typical large target such as an Agena spacecraft has a measured reflectivity pattern, as shown in Figure 7. When a large target is in motion relative to a radar, it is not

Table 3. Technical Risk Comparison of Microwave and Laser Radar Technology

Parameter	Microwave Radar	Laser Radar
Design/development problem	Assembly of system using well-proven techniques	Assembly of system from non-matured techniques
Availability of proven subassemblies and components	Multitude of past systems from which to choose (basically cata log items)	Transmitter and receiver components must be developed
Similarity to prior systems	Numerous aircraft radars and Gemini/Apollo space radars	Experimental systems only - no space experience
Production experience	30 years	None
Reliability	Experience allows confidence in MTBF - technology mature	Can only calculate MTBF - at start of maturity curve
Industry base	Many qualified companies	Few qualified companies
Recent programs	Problems found solvable	Several CO_2 programs cancelled prior to qualification
Detector problem	None	Shelf life; requires cryogenic cooling, very critical - unknown aging characteristics
Target	• Good history to assure ability to determine P_D • Target characteristics change very little with age	• Performance against irregular target not well predictable - target characteristics may change with age

possible to predict what part of the target is being illuminated. Furthermore, as the target moves, the illumination direction varies. Target cross section variation is referred to as "scintillation."

The magnitude of target cross section is a statistical variable, and in radar detection theory, it is defined ideally as an exponential probability density in power or a Rayleigh probability density in amplitude. In addition to the density functions, it is necessary to establish the rate at which the target produces a fluctuating return for a radar in search mode. Slow variations are defined relative to the angle search rate as those which are constant on one antenna angle scan but which vary from scan to scan. Rapid variations change fast enough that during the time the radar antenna beam illuminates the target several independent target amplitude samples are obtained. The two types of scintillation are referred to as Case I and Case II, after the work of P. Swerling.[1] The definition of a target model is an approximation but is a useful engineering procedure for determining required radar performance.

The significance of the two cases is that, for most detection situations, the target scintillates slowly and a Case I model applies. But Case II-that is, independent returns on a sample-to-sample basis-is advantageous when a high probability of detection is required in a short period of time. It has become the practice in search radar system design to induce rapid target fluctuation by incorporating frequency diversity in the radar. This has the net effect of changing the lobed structure spatial distribution of the target scattering pattern and thereby increasing the probability of obtaining one or more samples of target return during the time that the target is within the antenna beam. Target site or radar cross section is not increased, but the probability is greater that the target cross section is near the average on a single "look" or antenna dwell. The amount of frequency change necessary to obtain independence from pulse to pulse or pulse group to pulse group is determined by the power covariance function of the reflected signal. Decorrelated returns occur when this function is numerically small, and a change in frequency of $\Delta f \geq \frac{C}{2L}$ is used. C is the speed of light and L the target length. Thus, for a 10-meter target, the required frequency change is Δf = 15 MHz. This assumes that $L \gg \lambda$. Measurements on real targets using frequency diversity indicate that somewhat larger frequency shifts are required to obtain independent samples, so that shifts of the order of 25 to 50 MHz are used from sample to sample; and a total of five independent samples of frequency steps are used.

Target Search Requirements. Radar sizing is usually more sensitive to detection requirements than measurement accuracy, since if the required detection probability is high, a radar can track all closing targets detected. Target search limits the amount of energy reflected from a target as target location uncertainty is searched systematically. If the target is continuously illuminated, then the detection problem becomes trivial. The most significant effect of uncertainties encountered in rendezvous target acquisition is created by the angular position of the target relative to the Orbiter. For the long-range rendezvous mode, acquisition can be achieved by an angular scan of approximately ±20 degrees in each of two angular coordinates about the line of sight from the Orbiter to the target. This more than covers the three-sigma random angle errors as well as all systematic bias errors. Therefore, for long range rendezvous missions, the radar antenna searches an angular field of 40 by 40 degrees.

The effect of range uncertainty is relatively modest, and range search is not required. For the once-around mission, angle uncertainty can be quite large. For system sizing purposes,

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[1] P. Swerling, "Probability of Detection for Fluctuating Targets," IRE Trans Information Theory, Vol II-6; April 1960.

an angular search field of 90 by 90 degrees is used, although a decrease in navigation errors during the launch phase may permit a reduction of this value.

The effects of angle search on performance requirements are directly related to the time that a target is within the antenna beam, as the beam is systematically directed over the angular search field. The dwell time on the target can be shown to be given approximately by

$$\frac{E}{N_o} = \frac{P_t \, G^2 \lambda^2 \bar{\sigma} \, t_d}{(4\pi)^3 \, R^4 \, \overline{NF} \, K \, T \, L}$$

where:

- E - the received energy during the antenna dwell time, t_d
- N_o - the noise power density per H_z
- P_t - the average transmitted power
- G - the antenna peak gain
- λ - the wavelength of the transmitter signal
- $\bar{\sigma}$ - the effective radar cross section
- R - the range to the target

The value of the constant k is determined by the dual requirement of overlapping successive scan lines in the raster scan and the time required to stop the antenna on each scan line before commencing the next. For design purposes, the following values are used: elevation overlap - 30 percent and turnaround time - 20 percent per scan line.

For a given search frame time and total search field, the antenna scan rate is shown in Figure 8 with search field size as a parameter. The data are for a beamwidth of 2.76 degrees. For a real antenna, a practical upper limit exists on scan speed. The upper limit is not absolute, but a value of 120 degrees per second is used as a greatest upper bound. For the same antenna, the dwell time on a target is shown in Figure 9. Since long dwell times are advantageous, it follows that, as the search field increases, the frame time should be increased. The basic trade among scan speed, antenna beamwidth, and time on target presents a conflict, because the gain of a symmetrical antenna can be represented as

$$G = \frac{K_1}{\phi_3{}^2}$$

and if this is substituted into the expression for dwell time, then

$$t_d = \frac{K^1 \; t_f}{G \; \psi_\alpha \; \psi_\varepsilon}$$

This represents a basic conflict of high antenna gain and long target dwell time for a fixed frame time.

Installation Location on Orbiter. In contrast to the usual installation of fire control radar in aircraft in which the nose is a useful installation area, the Orbiter vehicle has no convenient volume for installing a high-gain antenna. This results primarily from the requirements for reentry, since most of the available vehicle surface area is covered with thermal protective material. This material is not transparent to microwaves, and the Orbiter nose, which would be a convenient location, would have to be opened for radar operation. This represents a flight safety problem, since reentry would not be possible with the nose open, and a heavy weight penalty caused by redundant closing mechanisms. The design philosophy has been extended to all of the principal surfaces of the vehicle, which obviates windows or doors for installing and deploying a high-gain antenna. An exception is the payload bay where doors are provided for payload deployment and retrieval during orbital operations. However, the payload bay is configured to hold the largest payload the Orbiter must carry into orbit for deployment and subsequent retrieval, and any deployable antenna cannot interfere with useful payload volume.

The installation dilemma was resolved, as shown in Figure 10, where an unfilled volume exists between the skin line of the largest payload and the payload bay door in the forward portion of the payload bay. The available volume is adequate for installation of a 20-inch diameter parabolic reflector on a two-axis gimbaled structure. To obtain adequate reflector illumination, a rear feed Cassegrainian antenna is used. The antenna shown was chosen to demonstrate the adequacy of the available installation volume, and further study may determine that an alternate design is more suitable. As currently configured, the antenna and all microwave components are located on a deployment boom, but only waveguide and receiver components are inside the gimbals so that rotary joints are required for the transmitted power. The use of the antenna for rendezvous in the position shown is adequate with the attitude of the Orbiter during rendezvous along the -Z body axis.

Radar Parameter Development. The characteristics of the rendezvous radar can be developed to a large extent independently of the modulation of the transmitted signal. This is especially true in target detection, which has a primary influence on radar system size. Although it is common practice to develop specialized forms of the radar equation, this approach creates difficulties when several mechanizations are to be compared. Therefore, for system sizing, it is desirable to keep the analysis as general as possible to determine a minimum set of characteristics before any attempt is made to particularize the radar design. This approach has been useful in the development of requirements for the rendezvous radar, since no selection of a design has been made. Basic to this is the assumption that all radar systems can possess the same design parameters such as antenna gain and noise figure and operating parameters such as wavelength, range, and target cross section. It is desirable to isolate the parameters likely to be different for a variety of radar designs. This approach results in a radar equation of the form

$$\frac{E}{N_o} = \frac{P_t\ G^2 \lambda^2 \bar{\sigma}\ t_d}{(4\pi)^3\ R^4\ \overline{NF}\ K\ T\ L}$$

where:

E - the received energy during the antenna dwell time, t_d

N_o - the noise power density per H_z

P_t - the average transmitted power

G - the antenna peak gain

λ - the wavelength of the transmitter signal

$\bar{\sigma}$ - the effective radar cross section

R - the range to the target

$\overline{NF}$ - the receiver noise figure

k - Boltzman's constant

T - the effective receiver noise temperature

L - the system losses

In this form, the equation gives the integrated signal-to-noise ratio used in detection probability calculations. All radars are definable in this form. Major differences occur in the time on target, t_d, and system losses, L. For a discrete sampled system such as a pulsed radar, it is the integrated signal-to-noise ratio resulting from the summation of the number of pulses of received signal exchanged with the target during the antenna dwell time. It points out specifically that target detection is a function of energy rather than power.

If the losses are restricted to real system losses, such as waveguide insertion loss, then the resulting signal-to-noise ratio is for a matched filter system known to be optimum. Specifically, if a detection threshold is set for a given probability of false alarm, then for a matched filter system, the ratio of received energy to noise power per Hertz establishes the probability of detection which cannot be improved. Real radar systems do not attain ideal performance, nor are target cross sections constant, so that the loss factor, L, must be increased depending upon the actual radar system mechanization and the target fluctuation loss. The loss mechanisms contained in L are determined by the radar mechanization and target characteristics. Typical loss factors are (1) all real system attenuations and insertion losses; (2) nonideal integration and detector losses; (3) detection threshold variations; (4) antenna beam shape (departure from assumed constant gain over the beamwidth); (5) nonideal IF bandwidth; (6) mechanization losses such as eclipsing in high PRF pulse Doppler; and (7) target fluctuation loss.

A detailed analysis of system losses is beyond the scope of this discussion, but it is in the area of system losses that much of the controversy arises in estimating system performance. Of particular concern are the losses associated with integration and detection and the reduction of target fluctuation loss by the use of frequency diversity. These points are discussed separately. The other losses have been estimated for system sizing purposes as follows:

Attenuation and insertion loss	3 dB
Threshold	1 dB
Antenna beam shape	1.6 dB
Nonideal IF bandwidth	1.0 dB
Total	6.7 dB

In addition, it is common practice to include an allowance for field degradation of up to 3 dB to account for nonideal operating conditions.

To account for integration and target fluctuation loss, it is first necessary to systematize the detection procedure. To accomplish this, an acceptable false alarm rate is first set, since detection of a signal in noise admits a false decision that a signal is present when, in fact, only noise is present. For sizing purposes, a false alarm rate of one per hour is used. The number of independent decisions in one hour is related to the system bandwidth, B, and the false alarm time, t_{fa}, by

$$P_{fa} = \frac{1}{t_{fa} B}$$

The probability of detection is then definable in terms of required signal-to-noise ratio and false alarm probability. Many sets of standard curves of probability of detection are available depending upon target definition. A typical set is shown in Figure 11[2] for a Swerling Case I target. The comparable curves for a nonfluctuating target are shown in Figure 12. The signal-to-noise values on the curves are numerics. For bandwidths encountered in radar, the value of false alarm probability falls between 10^{-6} to 10^{-10}. It can be seen from Figure 11 that for high probability of detection the false alarm probability is not a sensitive parameter.

Because of the short time available for detection, a high probability of detection is required. Overall, a detection probability of 0.99 is imposed as a requirement to assure a high probability of accomplishing rendezvous. Also, from a consideration of mission timeliness one minute is allocated for the required angle search. This can be divided into a

[2] W.M. Hall, “General Radar Equation,” Space/Aeronautics R and D Handbook; 1963, New York, N.Y.

number of search frames provided that actual antenna scan speed is kept below the maximum of 120 degrees/second. Then, for a number of frames, n, a cumulative probability of detection can be defined as

$$P_c = 1 - (1 - P_d)^n$$

where

P_c - the cumulative probability of detection
P_d - the single frame detection probability
n - the number of frames or opportunities to detect the target

For realistic antenna beamwidths and scan speeds, the number of frames is no more than two, and the required P_d is either 0.9 for two frames or 0.99 for one frame. For a P_{fa} of 10^{-9}, the required signal-to-noise ratio for a P_d of 0.9 is 200 (23 dB) for a fluctuating target and 39 (14.6 dB) for a nonfluctuating target. The difference is described as fluctuation loss. In this case, the fluctuation loss is 8.4 dB. But for 0.99 probability of detection in a single frame the fluctuation loss is 16.2 dB. Frequency diversity is applied to reduce fluctuation loss. The amount of loss reduction is difficult to establish. One procedures[3] recommended is to divide the fluctuation loss in dB by the number of independent steps. This is a heuristic approach, but it is borne out approximately by theoretical analysis.[4] However, for high probability of detection, a measurement program conducted by Westinghouse[5] indicates a maximum of approximately 10 dB improvement for a P_d of 0.99 for a frequency diversity bandwidth of 250 MHz . This is pessimistic compared to the Barton approach, since for P_d = 0.99, fluctuation loss, L_f, is 16.2 dB and for five frequency steps

$$L_f^1 = \frac{L_f}{5} = \frac{16.2}{5} = 3.65 \text{ dB}$$

an improvement of 12.6 dB. A realistic compromise appears to be the approach recommended by Barton up to the point that improvement is 10 dB and then the use of a maximum of 10 dB improvement.

The loss associated with post-detection integration is another way of expressing the well-known small signal suppression effect of rectification for detection. The resulting loss depends on input signal-to-noise ratio. Standard curves for determining integration loss are

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[3] D.K. Barton, "Simplified Procedures for Radar Detection Calculations," IEEE Trans-am Aerospace and Electron System, Vol. AES5, No. 5; September 1969; pp. 837-846.

[4] W.S. Burdic, Internal Technical Memorandum; March 1974.

[5] D.P. Tice, "The Effect of Frequency Agility on the Radar Detectability of Spacecraft," Westinghouse Electric Corp., Baltimore, Md.; September 1973.

given in the paper by D.K. Barton, as well as in most standard texts on radar detection. For a pulsed radar, it is necessary to know the actual number of pulses integrated before the effect of integration loss can be fully assessed. An illustration of this point are the data of Figure 13 from Barton's paper. The abscissa is entered at the number of pulses integrated or summed in the post-detection integrator. The parameter on the curves is the required signal-to-noise ratio for a given P_d and P_{fa} if a single sample is used in the detection process. These data are obtained from Figure 11 or 12, depending on the target model. The integration loss is then read from the ordinate. However, for most radar mechanizations the number of pulses integrated is between 50 and 200, and the resulting integration loss for a single sample of 14 dB is approximately 5 dB. This value is used for sizing purposes and can be verified once a firm mechanization is established. The losses are summarized in Table 4 for single scan detection probabilities of 0.9 and 0.99. For power requirement calculations, the values with frequency diversity are used.

Table 4. System Loss Summary (values in dB)

Loss	P_d = 0-9		P_d = 0-99	
	Without Freq Div	5-Step Freq Div	Without Freq Div	5-Step Freq Div
System	6.7	6.7	6.7	6.7
Integration	5.0	5.0	5.0	5.0
Fluctuation	8.4	1.7[(1)]	16.2	6.2[(2)]
Total	20.1	13.4	27.9	17.9

(1) $\frac{8.4 \text{ dB}}{5} = 1.7$

(2) 16.2-10 = 6.2

Radar system sizing is a matter of routine once the losses are established. The question of operating frequency was originally based on the use of a sufficiently high frequency to obtain both a high antenna gain and acceptable angular accuracy within the limits of available components such as transmitter tubes and reasonably low noise receivers. The original choice of frequency band was 16 to 17 GHz, but this was reduced to 15 GHz when wideband data communication was added. At 15 GHz, the following system parameters were established as reasonable design goals using available technology.

Noise figure	8 dB
Antenna gain	35.4 dB (antenna dia 20 inches)
Antenna beamwidth	2.76 degrees

In radar system design a standard temperature of 290°K is commonly used. For an average radar cross section of one square meter and a Swerling Case I target with frequency diversity, the system parameters are summarized in Table 5 and the calculation of average power required is given in Table 6. The long-range rendezvous missions and the short-range Mission III-B power requirements are essentially identical. As pointed out previously, it is common practice in radar system design to allow up to 3 dB for field degradation, so that actual average transmitter power has been set at 40 watts and the system sized accordingly.

Table 5. Radar System Parameters (values in meters)

Parameter	Numeric Value		dB Value	
Fixed				
Antenna gain (η = 0.55)	3.46×10^3		35.4	
λ	2×10^{-2} m		-17	
σ	1 m^2		0	
$(4\pi)^3$	1.98×10^3		33	
$\overline{NF}$	6.3		8	
K	1.38×10^{-23}		-228.6	
T	290° K		24.6	
	Long Range	Mission III-B	Long Range	Mission III-B
Mission dependent				
t_d	80×10^{-3} sec (2)	33×10^{-3} (3)	-11	-15
R	22,224 m	12,964 m	43.5	41.1
L	2.18×10 (1)	6.15×10 (1)	13.4	17.9

(1) One minute detection
(2) Two search frames - 40 by 40 degrees P_o = 0.9 per frame
(3) One search frame - 90 by 90 degrees P_o = 0.99

Table 6. Average Power Requirements

	R = 12nm, P_d = 0.9, S/N = 14.6 dB		R = 7nm, P_d = 0.99, S/N = 15.8	
S/N Rqd	14.6		15.8	
$(4\pi)^3$	33		33	
R^4	174		164.4	
$\overline{NF}$	8		8	
K		228.6		228.6
T	24.6		24.6	
L	13.4		17.9	
G^2		70.8		70.8
λ^2	34		34	
σ		0		0
t_D	11		15	
	312.6	299.4	312.7	229.4

R = 12 nm	R = 7nm
P_t = 312.6 - 299.4 = 13.2 dBW	P_t = 312.7 - 229.4 = 13.3 dBW
P_t = 21 Watts	P_t = 21.4 Watts

Parameter Measurement Accuracy. Radar measurement accuracy is determined essentially by the signal-to-noise ratio and the mechanization used. When accurate angle estimation is required, a monopulse antenna system is used. When both position and the rate of change of position are required, it is common practice to mechanize the parameter measurements separately. Angle position data are measured indirectly by angle "pick-off's" on a tracking antenna structure, and separate pick-offs are used for angle rate. The radar acts as an angle error detector to generate drive signals to antenna servos. Angle accuracy is dependent upon three essential characteristics: the antenna beamwidth, the signal-to-noise ratio, and the error slope of the angle error detection characteristic of the antenna. For the antenna beamwidths at 15 GHz and 20-inch antenna diameter, antenna angle and angle rate accuracies can be met without difficulty.

When the radar measures parameters directly as with range and range rate a conflict occurs. Theoretically, range and range rate can be measured simultaneously by judicious design of the radar transmitted waveform. Practically, however, it is common to optimize the waveform for either direct range or velocity measurement and derive the associated parameter. For typical pulse radar, the range is measured directly and the range rate is determined by differentiating the range. In a pulse Doppler radar, the velocity is measured directly and range is determined by the solution of an algorithm for resolution of range ambiguity. An alternative method in a high pulse repetition frequency Doppler radar is to use a more complex waveform for the transmitted signal and measure range and range rate simultaneously.

It is at least theoretically possible to meet range and range rate accuracy requirements with a conventional pulse system provided that range rate data are smoothed sufficiently. But smoothing requires data delay, so that output velocity may lag actual velocity by as much as two seconds following an acceleration. The required value of σ_R is 0.33 ft/s, and a smoothing time of approximately 3.7 seconds is indicated. A data delay following an acceleration would be approximately one-half the smoothing time, or two seconds. The acceptability of this delay remains to be demonstrated.

With Doppler velocity measurement the smoothing time is of the order of 0.25 second, and a much shorter delay is obtained following an acceleration. The choice of a Doppler or conventional pulse system is still under study.

Rendezvous Sensor Characteristics. The significant characteristics of the rendezvous radar that impact the installation and use of the sensor on the Orbiter are given in Table 7. It would be premature to define a mechanization in detail. Based on performance requirements and Orbiter interfaces, it has been possible to establish size and form factors for the radar to an extent that permits orderly development of the Orbiter vehicle.

Table 7. Significant Radar Characteristics

Antenna:	
Diameter	20 inches
Feed	Cassegrainian
Angle tracking	4-horn monopulse - amplitude-amplitude
Beamwidth	2.76 degrees
Gain	35.4 dB
Location	Deployed on boom
Gimbals	2 axis
Operating frequency	15 GHz nominal
Frequency diversity	250 MHz in 5 steps
Transmit power	40 Watts average
Transmitter cooling	Radiative
Total power	600 Watts

The radar as installed in the Orbiter is divided between a deployed assembly and an electronic assembly. It is installed in a controlled environment outside of the payload bay. The total installed weight is in the range of 150 pounds.

Conclusions. Design and trade studies have been conducted on the impact of a rendezvous sensor for the Space Shuttle Orbiter vehicle. To minimize technical risk, a microwave radar was chosen. The performance requirements for the rendezvous radar are similar to airborne fire control radar except that the detection probability is substantially higher. This follows from the fact that a high probability of success of the rendezvous mission is required.

The general form and principal characteristics of the rendezvous radar are defined, so that adequate provision can be made on the Orbiter vehicle at an early stage in the vehicle development. The actual mechanization of the radar has not been selected, but the simultaneous measurement of range and range rate to a high level of accuracy can be expected to add complexity to the radar.

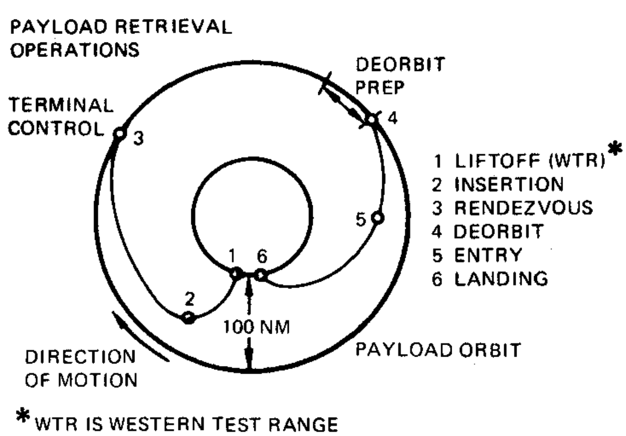

Figure 1. Mission III-B Orbital Geometry

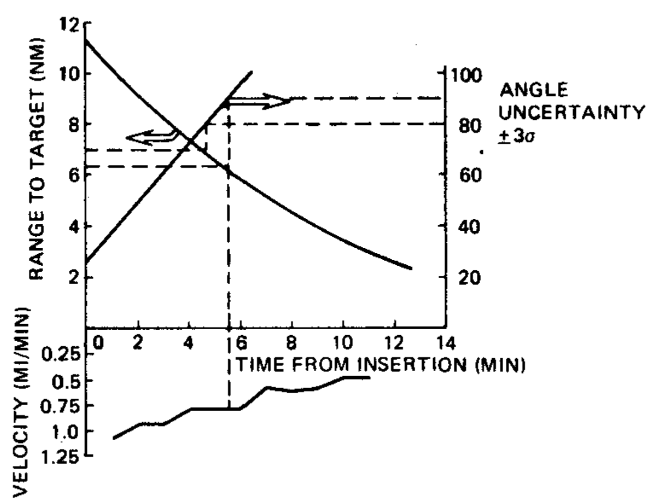

Figure 2. Mission III-B Dynamics Relative Motion

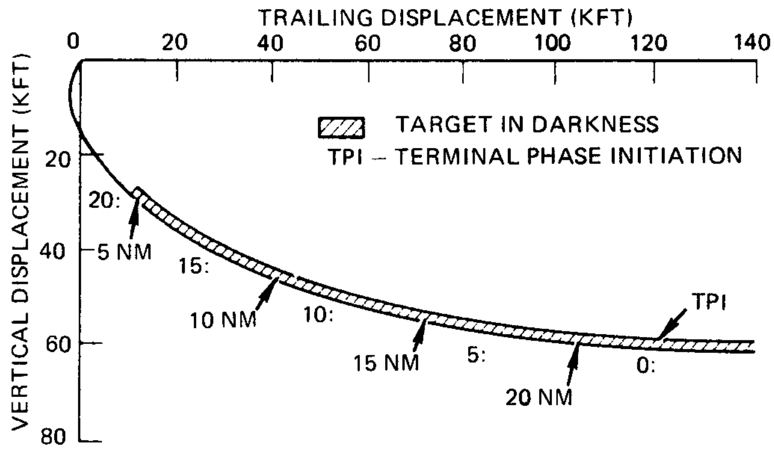

Figure 3. Nominal Long-Range Rendezvous Profile

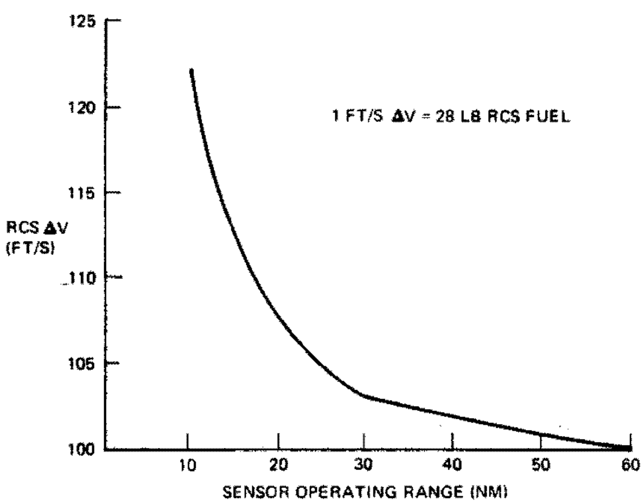

Figure 4. Long-Range Rendezvous RCS ΔV Required as a Function of Sensor Operating Range

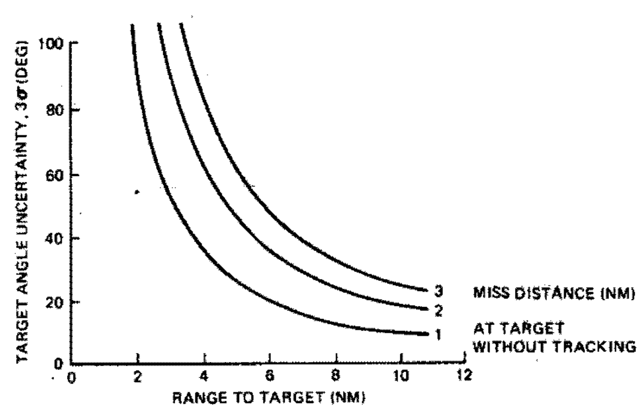

Figure 5. Long-Range Rendezvous Terminal Phase Angle Uncertainty

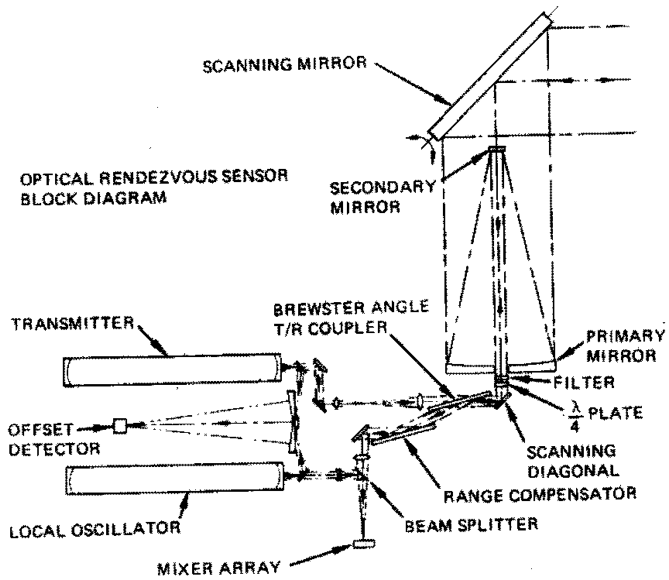

Figure 6. Optical Schematic of CW Laser Radar

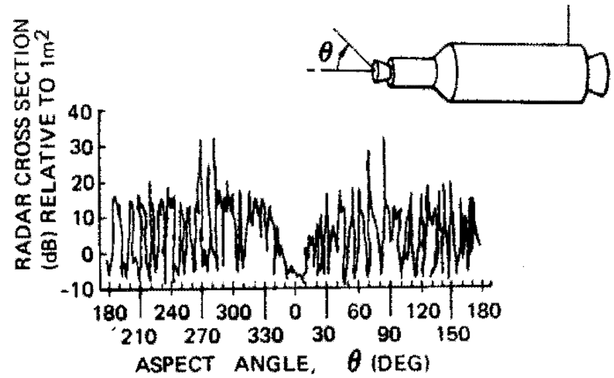

Figure 7. Measured Radar Cross Section of Agena Spacecraft at X Band

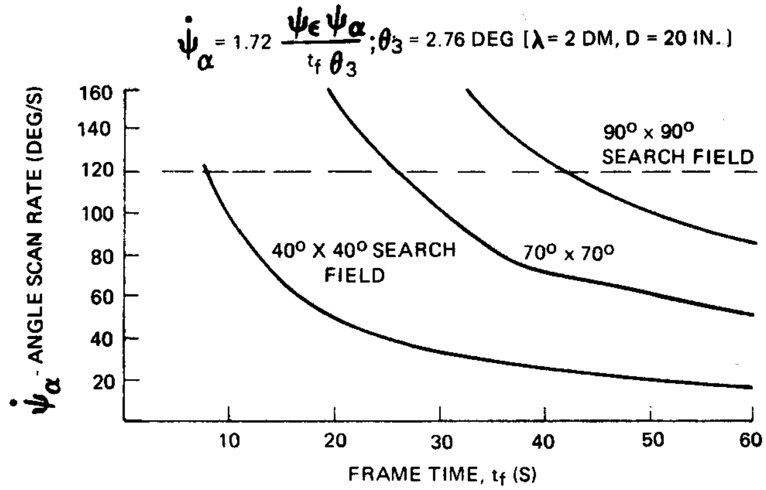

Figure 8. Required Angle Scan Rate

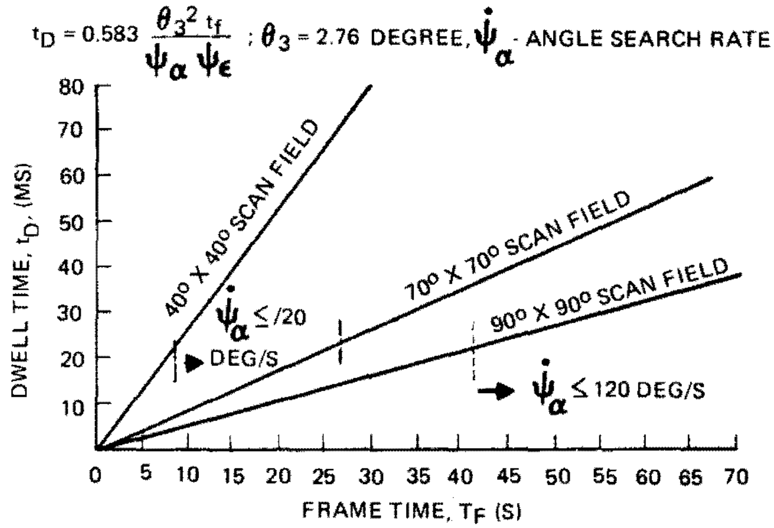

Figure 9. Target Dwell Time in Search Beam Width

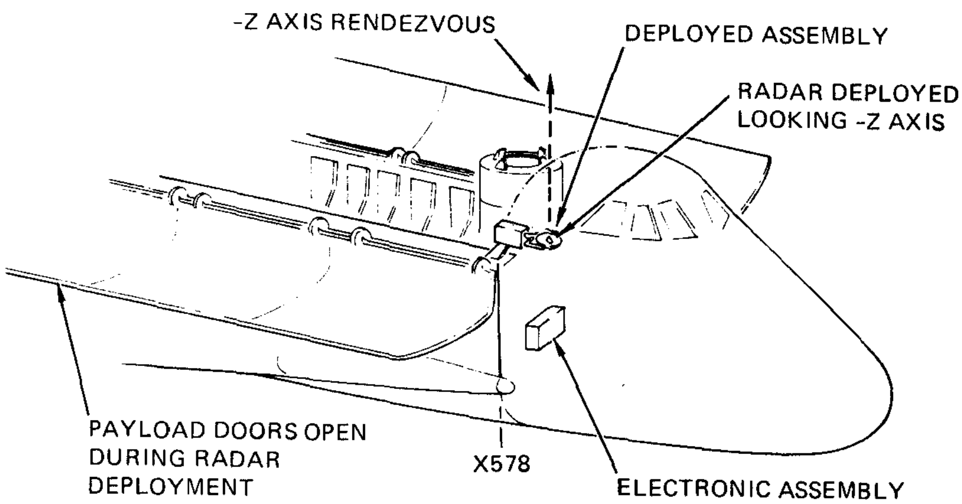

Figure 10. Rendezvous Radar

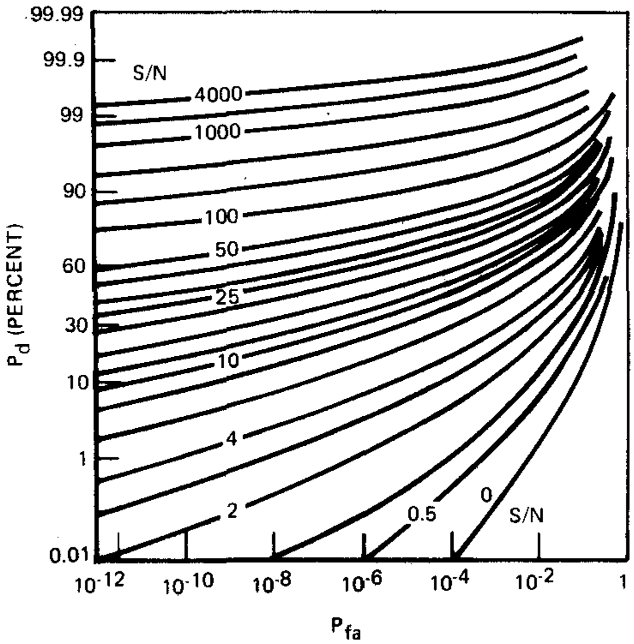

Figure 11. Probability of Detection Versus False Alarm Probability for a Swerling Case I Fluctuating Target

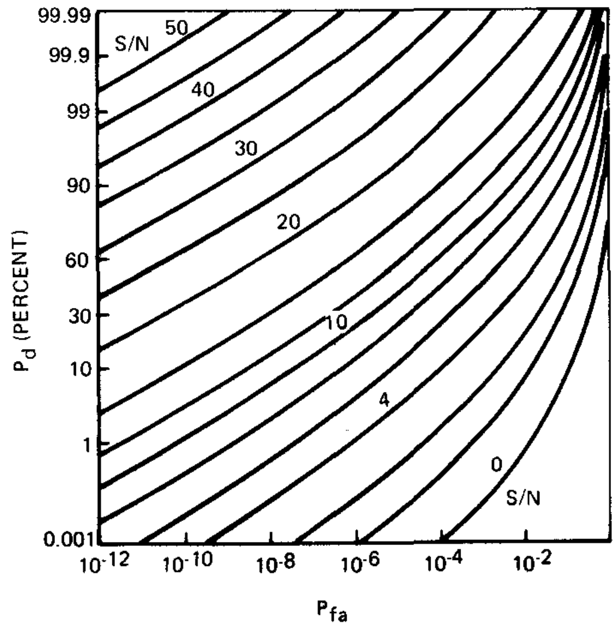

Figure 12. Probability of Detection of a Steady-Target Versus Probability of False Alarm

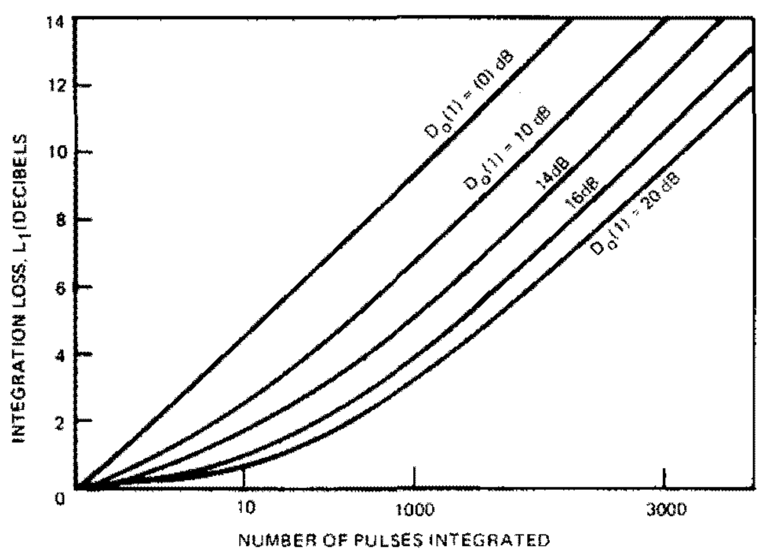

Figure 13. Integration Loss Versus Number of Pulses Integrated for Different Values of Single-Pulse SNR